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MILLIMETER WAVE RADAR SYSTEM CONCEPT STUDY - - PHASE I

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This report represents the first phase of a three-phase concept study that is intended to produce a "paper" design of a radar system capable of tracking low-flying subsonic aircraft at millimeter wave frequencies.

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INTRODUCTION

Background

In this report, the first phase of a three-phase concept study is represented that is intended to produce a "paper" design of a radar system capable of tracking low-flying subsonic aircraft at millimeter wave frequencies. The purpose of the system is to improve the ground-based air defense capability of tracked vehicles. The radar system to be initially developed will be an experimental model that will demonstrate the feasibility of the system.

In this interim report, the SEMCOR concept of the radar system is presented. The next report, representing the second phase of the study, will be an analysis of the Army's radar-system concept. In the final report, representing the third phase of the study, the selected system chosen will be presented for implementation as a result of the trade-offs required to achieve the best possible composite radar system as determined by the first two phases of the study.

The design details contained in this report include system-level trade-offs with block diagrams to the subsystem level. The system designs were developed largely on the basis of operational and technical requirements supplied by the Army.

Although almost all requirements were stated, some requirements were implied and, thus, became evident during the system concept development. For example, a 360-degree search-while-track capability, although not directly stated, is a virtual necessity in a multitarget tactical environment. This requirement alone restricts the concept development to either one complex, multifunctional radar capable of track while scan, or two simpler radars, each dedicated to either the search or tracking function. The latter configuration was selected for analysis on the basis of simplicity and ease of implementation. The stated operational and technical requirements will be presented later in this report.

Approach

To develop the system concept, the stated requirements were considered, the state of the art was surveyed to identify existing components at the frequencies of interest, and the required trade-offs were made to meet the performance goals. This effort resulted in a recommended configuration for both the search and the tracking radars.

After the desired system reaction time, system complexity, and designation accuracy were considered, the beam for the search radar configuration was recommended to be 2.5 degrees in azimuth and 6 degress in elevation to provide an elevation data input to the tracking radar. Further, consideration of clutter effects resulted in the recommendation of a double-delay canceler to remove stationary targets and clutter. Blind speeds were to be removed by the staggering of two PRF's at ten-pulse intervals.

The recommendations for the tracking radar configuration include a 0.5-degree x 0.5-degree pencil beam to optimize the scan rate and clutter effects, a digital filter bank (FFT and integrator) to provide clutter rejection and coherent integration gain, an adaptive threshold to maintain dynamic range, and a Cassegrain antenna configuration to minimize waveguide lengths. Finally, blind speeds are to be removed by the staggering of four PRF's on a pulse-to-pulse basis.

Once the tracking radar is implemented, some initial tests should be conducted to include such measurements as clutter effects, multipath characteristics, and ducting. In addition, further detailed study should be pursued to optimize the implementation of such items as the FFT and the adaptive threshold. Further development is required in component technology at millimeter-wave frequencies, particularly in coherent oscillators.

Finally, the implementation effort should be concentrated on the track radar to demonstrate feasibility as early as possible.

Report

This interim report deals with the following aspects of the radar system: operational considerations, system requirements, search radar design, and track radar design.

Operational considerations deal with the threat characteristics and the operational environment against which the radar system must eventually operate.

System requirements deal with the technical requirements of the radar system as a result of the operational considerations.

Search radar design deals with various trade-off options for the search radar in terms of hand-off capability to the track radar and performance.

Track radar design deals with the trade-offs that pertain to the track function, such as acquisition and track capability given various hand-off procedures as well as system performance against various conditions.

OPERATIONAL CONSIDERATIONS

The radar system should perform adequately against three types of threats. The highest priority threat is the low-flying Mach I aircraft. The other two threats are the helicopter and the antiradiation missiles.

The flight profile of the Mach I aircraft allows an altitude variation from 6 meters to approximately 6000 meters. The low-altitude portion of this range (approximately 6 to 60 meters) presents the greatest strain on radar system performance as a result of clutter and multipath problems. The Mach I velocity constrains the available system reaction time. Because of the velocity and the low-altitude characteristics, the radar system was designed with this threat primarily in mind.

The helicopter threat presents a different set of conditions. The helicopter is capable of extremely low-altitude flight at zero radial velocity. Further, it is capable of hiding itself behind tree lines for very long periods of time. Although its size (in terms of radar cross section) is much larger than the other two threats, its versatility in concealing itself behind foliage makes it a very difficult target to detect. Previous studies have shown, however, that the rotation of the helicopter rotor can be tracked behind trees at W-Band frequencies. Since the helicopter is essentially a stationary target under most operational conditions, it was considered a relatively less dangerous threat than the Mach I aircraft.

At this point, detection and tracking of the ARM (Antiradiation Missile) threat was considered a desirable but not required capability of the radar system. Consequently, the scan coverage of the search radar was defined to include this threat, but the analysis of radar performance is based on the cross section of the Mach I aircraft.

In addition to detecting and tracking the threats described above, the radar system must perform adequately in the presence of rain, fog, and smoke, and against various conditions of ground clutter and multipath.

The rain requirement was defined by the Army in millimeters/hour. No specific requirements were defined for fog or smoke.

Further, the radar system must eventually be capable of operating in all types of terrain anywhere in the world. As a result, ground clutter and multipath interference must be considered under this general condition.

In addition, the radar system should be capable of simultaneous search and track. The desired azimuth search coverage is 360 degrees. This condition implies either one radar with a track-while-scan capability or two radars, one dedicated to search, the other to continuous tracking. Implicit in this requirement is the desire of the Army to demonstrate and to further develop millimeter wave technology. With this in mind, in addition to the considerations of cost and simplicity, the designs in this report are based on two radars at frequencies designated by the Army. These were determined to be 9 GHz for search and 94 GHz for track.

As a result of the above considerations, the threat and environment requirements were summarized in table 1.

Table 1. Threat and environmental requirements

Parameter	Requirement
<u>Threat</u>	
Cross section	1 m^2
Type	Swerling Case I
Range rate	0-310 m/sec
Altitude	6-6000 m
Minimum engagement range	500 m
Minimum unmasking range	8 km
Reaction time*	10 sec
<u>Environment</u>	
Rain	4 mm/hr
Ground clutter	Any terrain possible

*Time that target enters Search Radar Detection range (envelope) to the ready-to-fire time.

SYSTEM REQUIREMENTS

From the operational requirements, as many of the technical requirements of the radar system were defined as possible. These requirements are given in table 2.

Table 2. System requirements

Radar Parameter	Requirement
<u>Search</u>	
Probability of detection	0.9
Detection range	12 km
Probability of false alarm	10^{-6} (CFAR)
Spatial coverage	
Elevation	30 deg. minimum
Azimuth	360 deg.
Frequency	9 GHz
Antenna size	1 m nominal
Range resolution	150 m minimum
Output data	Range, azimuth, elevation (desirable)
<u>Track</u>	
Probability of detection	0.9
Probability of false alarm	10^{-6} (CFAR)
Spatial coverage for acquisition	Search window within the designation data of the search radar
Tracking limits	

Table 2. System requirements (Continued)

Radar Parameter	Requirement
Track (Continued)	
Frequency	94 GHz
Antenna size	1 m nominal
Track accuracy	1 milliradian rms.
Output data	Range, range rate, azimuth, azimuth rate, elevation, elevation rate
Range resolution	75 m minimum

With the operational and the system requirements defined, both radars were designed and are presented in the succeeding sections. These designs were developed to minimize complexity, to perform consistently, to maximize reliability, and to reduce costs.

SEARCH RADAR DESIGN

Requirements

The requirements for the search radar system are:

Volumetric coverage, 360-degree azimuth x 30-degree elevation (minimum) x 12 kilometers range.

Detection range, 90 percent probability of detection of 1 meter^2 Swerling Case I target at 12 kilometers.

Range resolution, 150 meters (minimum).

Velocity coverage, 0 meters per second to 310 meters per second.

Altitude coverage, six meters to 6000 meters.

Environmental conditions, minimum degradation is 4 millimeters per hour rain rate; operation in all types of terrain; constant false alarm rate operation; probability of false alarm is 10^{-6}.

Additional requirements and limitations placed on the search radar system are:

The track radar system must be designated to the target position (range, azimuth, and preferably elevation) in a timely manner.

Maximum antenna aperture dimension should be approximately one meter.

Maximum frame time (complete volumetric coverage) should not exceed 6 seconds.

The antenna aperture size limitation indicates operation at X-Band frequencies (9 to 10 Gigahertz) to achieve the antenna gain necessary to meet the detection requirements. A survey of the literature revealed that a typical transmitter output tube for coherent operation at X-Band frequencies is a Klystron tube supplying 50 kilowatts of peak power with a 0.008 duty cycle, e.g., the Varian VA-24E. These are the parameters used in the search radar system design calculations.

The range resolution requirement of 150 meters requires a maximum pulse width (τ) of one microsecond (no pulse compression), and the duty cycle of 0.008 accommodates a maximum pulse repetition frequency(PRF) of 8000 pulses per second (PPS) (duty cycle = $\tau \cdot$ PRF). This PRF gives a maximum unambiguous range of 18.75 kilometers.

Detection range is a function of the product of average transmitted power and antenna aperture area. When limitations are placed on these two parameters through peak power, duty cycle, and aperture size, detection range must be considered within the constraints of other system requirements. For example, the radar designer might be inclined to make maximum use of a given aperture

size by achieving the maximum antenna gain, but this would also constrict the antenna beamwidth and would require more scans to cover the required search volume. The increased number of scans, expecially for a mechanically scanned antenna, may require an unacceptable time frame or, alternatively, an increased scan rate may not provide a sufficient number of hits per point target with which to achieve an acceptable detection range.

Search Radar System Trade-Offs

The radar range equation used in the design calculations is

$$S/N \text{ (single hit)} = \frac{P_t\ G^2\ \lambda^2\ \sigma}{(4\pi)^3\ R^4\ L_s\ K\ TB\ \overline{NF}} \quad \text{where}$$

P_t = Peak transmitter power = 50 KW = 47 dB

G = Antenna gain (common antenna for transmission and reception

λ = Wavelength = 0.033 m; λ^2= 0.0011 m^2 = -29.5 dB

σ = Target cross section = $1m^2$ = 0.0 dB

R = Target range = 12 km; R^4 = 2.0736 x 10^{16} m^4 = 163.2 dB

L_s = Total system losses

K = Boltzman's Constant = 1.38 x 10^{-23} Joules/^{o}K

T = System temperature in degrees Kelvin = 290^o

B = Receiver noise bandwidth = $\frac{1}{\tau}$ = one MHz = 60.0 dB

$\overline{NF}$ = Receiver noise figure (assumed to be 6.0 dB)

$(4\pi)^3$ = 1984.4 = 33.0 dB

S/N = Signal-to-noise power ratio

Expressed in dB and with the above parameters, the single hit signal-to-noise ratio reduces to:

$$S/N\ (dB) = -40.7 + G^2 - L_s$$

Single Fan Beam Scanned in Azimuth

As shown in Figure 1, a 30-degree elevation beamwidth will allow altitude coverage to approximately 6.2 kilometers at a 12-kilometer range. However, a target advancing at a constant altitude of 6 kilometers will be within the elevation beam coverage at approximately 11 kilometers.

To fill in the blind spots at high altitudes and ranges of less than 12 kilometers, a cosecant^2 beam pattern to a 45-degree elevation is recommended.

The antenna aperture should be illuminated with a cosine^2 distribution to reduce the antenna sidelobes. The cosine^2 distribution will provide sidelobes 32 dB less than the peak antenna gain. The half-power antenna beamwidth will be 83 λ/a where a is the aperture dimension, and the aperture efficiency will be 0.667 (ref 1).

With these factors for a fan beam with a shape of 2.5 degrees in azimuth and 30 degrees in elevation, the aperture required will be 1.107 meters (43.57 inches) x 0.092 meter (3.63 inches). The antenna gain is given by the equation:

$$G = \frac{4 \pi A \eta}{\lambda^2}$$

where

A is the aperture area

η is the aperture efficiency

λ is the wavelength

$$G = \frac{4 \pi \times 1.107 \times 0.092 \times 0.667}{0.0333^2} = 769.5 \text{ or } 28.86 \text{ dB}$$

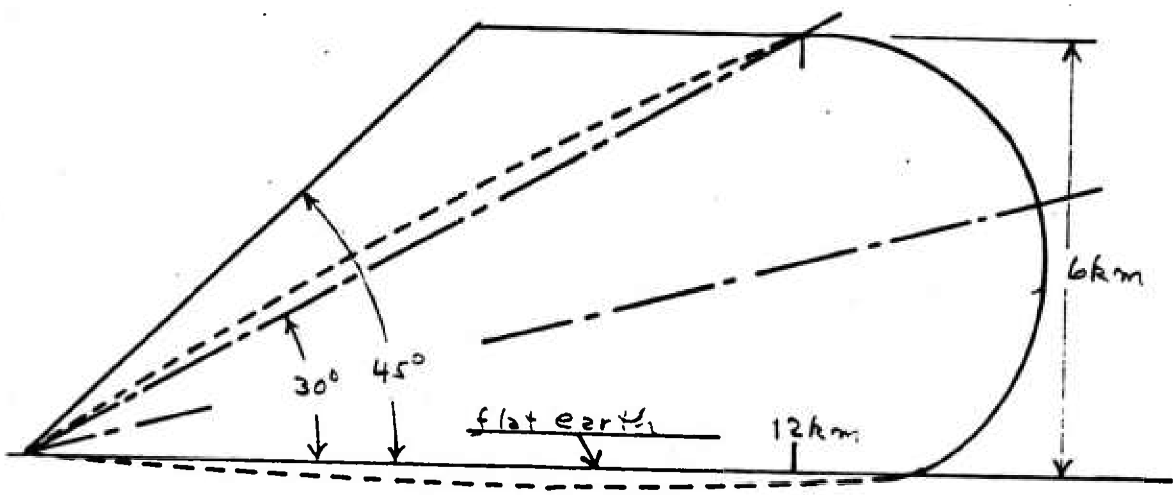

Figure 1. Single fan beam antenna elevation pattern.

The gain loss encountered due to the cosecant^2 beam-shape is given by (rep. 2).

$$G/G_c = \frac{\theta_o + \sin^2 \theta_o \ (\cot \theta_o - \cot \theta_m)}{\theta_o}$$

For $\theta_o = 30^\circ$ and $\theta_m = 45^\circ$ $G/G_c = 1.35$ or 1.30 dB

Thus the gain of the cosecant^2 beam-shape antenna is 27.56, or approximately 27.6 dB, giving coverage to a 45-degree elevation.

The system losses are assumed to be:

Transmit	2.5 dB
Receive	2.0 dB
Beam shape	1.6 dB
Atmospheric	0.3 dB
Total	6.4 dB

The single-hit signal-to-noise ratio in a clear environment is then:

$$S/N = -40.7 + 55.2 - 6.4 = 8.1 \text{ dB}$$

Attenuation due to a four mm/hour rainfall is assumed to be 4×10^{-2} dB/kilometer (ref. 3). Thus, for a round-trip path of 24 kilometers, the total attenuation will be 0.96, or approximately one dB. The single-hit signal-to-noise ratio in a 4 mm/hr rainfall will then be 7.1 dB. The 7.1 dB signal-to-noise ratio is not sufficient to provide a 0.90 probability of detection.

If the antenna is scanned at the rate of 30 RPM (180 degrees/second), a 2.5-degree azimuth beamwidth will dwell on a point target for 0.0139 second. An 8-kHz PRF will allow 111 hits. If the 111 target returns were coherently integrated, the improvement factor would be 20.46 dB that will provide an effective signal-to-noise power ratio of 27.6 dB. This is more than sufficient

to achieve a probability of detection of 0.90. Even a noncoherent integration of 111 pulses will provide an integration gain of 15 dB that will give an effective signal-to-noise power ratio of 22.1 dB. This is sufficient to achieve a probability of detection of 0.90. (A noncoherent integration of 111 target returns with an input signal-to-noise ratio of 7.1 dB will achieve a probability of detection of 0.90 with a probability of false alarm of 10^{-6}) (ref 4).

The track-acquisition volume will be 2.5 degrees x 30 degrees x 150 meters since this search system can designate the track system in only azimuth and range. If the track antenna beamwidth is 0.5 degrees 300 track-beam positions will be within the acquisition volume. On the assumption of an average track scan rate of 13.8 degrees/second, 11 seconds will be required for the track radar to scan the acquisition volume. During this time interval, 5.5 search radar scans will occur.

Dual Simultaneous Fan Beams

The elevation pattern for the dual fan beam antenna is shown in figure 2. No cosecant^2 beam shape will be used since the purity of both beams will be maintained for comparison of target return signal amplitudes.

A single truncated parabolic aperture will be illuminated by two offset horns with a cosine^2 distribution. Thus, the beamwidth and aperture efficiency factors of the single-fan beam antenna also apply to the dual-beam antenna. The sidelobes of the dual-beam antenna will be approximately 32 dB less than the peak antenna gain.

Each beam of the dual beam antenna will be 2.5 degrees in azimuth and 15 degrees in elevation. This will require a 1.107-meter (43.57 inches) x 0.184-meter (7.26 inches) aperture. The gain of this aperture at 9 Gigahertz will be 1539.02, or 31.9 dB.

The assumption is that the transmitter power will be split (three dB) and simultaneously fed to each horn. With one dB of loss allowed for the power split, each beam will be fed with 43 dB of power. The equation for the single-hit signal-to-noise power ratio (per beam) then becomes:

$$S/N\ (\mathrm{dB}) = -44.7 + G^2 - L_s$$

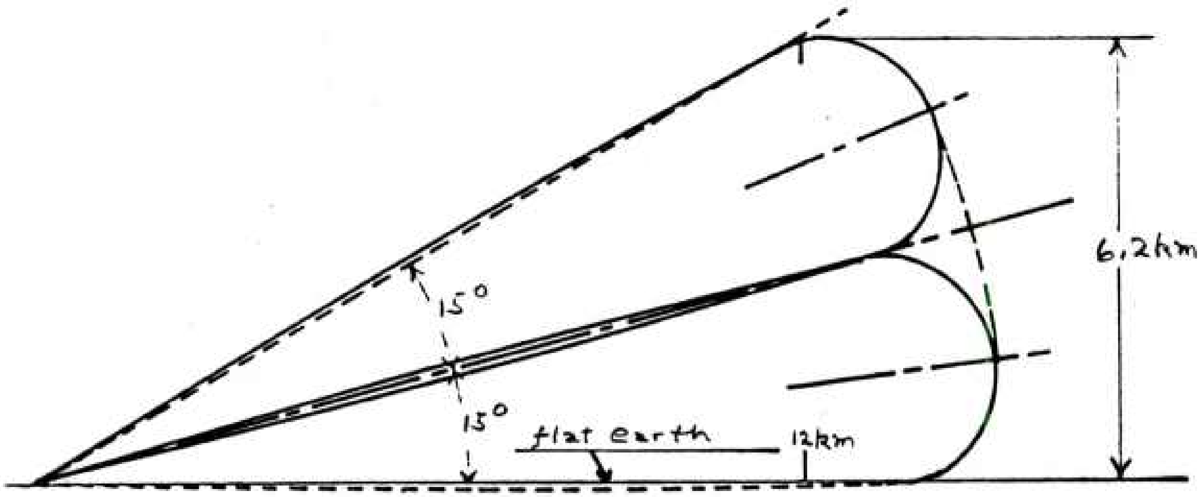

Figure 2. Dual simultaneous fan beam antenna elevation pattern.

Assuming the same system losses per beam (6.4), one finds that the single-hit signal-to-noise power ratio of the dual-beam search radar system will be:

$$S/N \text{ (single hit)} = -44.7 + 63.8 - 6.4 = 12.7 \text{ dB}$$

In a 4 mm/hr rainfall, the single-hit signal-to-noise power ratio will be reduced to 11.7 dB.

The probability of detection for a single hit with a signal-to-noise power ratio of 11.7 dB is approximately 0.55. The cumulative probability of detection (no integration) of three such hits will be approximately 0.91. If the antenna is scanned at the rate of 60 RPM (360 degrees/second) and if each beam is sampled on alternate pulses, the effective number of hits per point target will be 27. This number of hits will give a coherent integration gain of 14.3 dB and a non-coherent integration gain of approximately 11.1 dB. Either improvement is more than sufficient to achieve a probability of detection of 0.90. (A noncoherent integration of 20 target returns with an input signal-to-noise ratio of 11.7 dB will achieve a probability of detection of 0.90 with a probability of false alarm of 10^{-6} (ref 4).

The purpose of using the dual-beam antenna is to derive elevation information from the target returns. Two means of deriving the elevation information are considered. One means would be to sum and difference the received outputs of the two duplexers (a duplexer will be located in each feed of the antenna system) and to use a monopulse technique to derive the elevation information. This technique would require two receiver systems (mixers and IF amplifers). The other means of deriving the elevation information would be to multiplex the received outputs of the two duplexers to a single-receiver system. The comparison of the two techniques of deriving elevation information is a comparison of simultaneous lobing (monopulse) and sequential lobing. The error voltage slope for a three-dB beam crossover is the same for both techniques (ref 5). Therefore, to reduce the equipment required, the multiplexing technique is recommended.

The full advantage of the elevation-error voltage can be achieve only at target elevations between the beam centers, or at target elevations between 7.5 degrees and 22.5 degrees. Within this region, the track radar can be designated in elevation to

within ± 1 degree. For the upper and the lower 7.5 degrees of elevation that must be covered, beam slicing could be used (multiple thresholds with only one beam providing crossover). The expectation is that the track radar could be designated to within three degrees in elevation with this technique. Again, assuming an average track-radar scan rate of 13.8 degrees/second, one finds that the acquisition time would be reduced to about 1.1 second (maximum). The maximum acquisition time of the track radar would be about 2.72 seconds without beam slicing of the upper and lower 7.5 degrees of the coverage.

Single Fan Beam Scanned in Elevation

With the same cosine^2 distribution criteria for the antenna parameters as before, a 2.5-degree azimuth x 6-degrees elevation beamwidth will require an antenna aperture of 1.107 meters (43.57 inches) x 0.461 meter (18.15 inches). An aperture this size will provide a gain of 35.85 dB.

The antenna will be scanned in azimuth at a rate of 60 RPM (360 degrees/second) and in elevation at a rate of 6 degrees/second, thus giving complete coverage from a 0-degree elevation to a 36-degree elevation in a frame time of 6 seconds. A target starting at 12 kilometers at a constant velocity of 310 meters/second and a constant altitude of 6 kilometers will take 12.1 seconds to reach the blind area with a 36-degree elevation coverage (8.26 kilometers horizontal range). With a 6-second time frame, 12.1 seconds will allow two scans past the target.

The system losses will be increased to account for the additional elevation joint and the two-directional beam-shape loss. The resulting system losses are:

Transmit	3.0
Receive	2.5
Beam Shape	3.2
Atmospheric	0.3
Total	9.0 dB

The resulting equation for the single-hit signal-to-noise power ratio becomes:

S/N (single hit) = -40.7 + 71.7 - 9.0 = 22.0 dB

In a 4 mm/hr rainfall, the single-hit signal-to-noise ratio will be reduced to 21.0 dB.

A 21.0 dB signal-to-noise ratio will produce a single-hit probability of detection of 0.90 with a false alarm probability of 10^{-6} (ref 4).

With an antenna azimuth scan rate of 360 degrees/second, a 2.5-degree azimuth beamwidth will dwell on a point target 0.0069 second, and with an 8 kHz PRF, 55 target returns will be recieved.

The acquisition volume for a 2.5-degree x 6-degree search radar beamwidth is 60 track radar beam positions of 0.5 degree each. With an average scan rate of 13.8 degrees/second, the acquisition time will be about 2.2 seconds.

Other Considerations

A number of pulses must be integrated for the single 30-degree elevation fan beam and the dual-beam search radars to achieve a probability of detection of 0.90 in a 4 mm/hr rainfall. The presence of clutter will also obscure the target unless clutter suppression is used to provide subclutter visibility.

Volume Clutter

The volume clutter considered will be due to a 4 mm/hr rainfall. This rainfall will be considered homogenous and will extend for a radius of at least 12 kilometers and to an altitude of 6 kilometers. (The attenuation due to rain used in the calculation of signal-to-noise ratios was derived from the same model). The entire beam is filled with rain. The backscatter area will depend on the volume inclosed in one range resolution element ($R^2 \theta_a \theta_e c \tau/2$) and the backscatter coefficient of the

rain. The backscatter coefficient of 4 mm/hr rainfall at 9 Gigahertz is assumed to be 7×10^{-7} m^2/m^3 (ref 6). The backscatter areas of the three beamshapes in four mm/hour rain at 12 kilometers is calculated to be:

Single 30-degree elevation fan beam - 25.4 dB

Dual fan beam - 22.4 dB/beam

Single six-degrees elevation fan beam - 18.4 dB

Since the backscatter areas are referenced to 1 m^2, the backscatter area in dB is the amount of clutter suppression required to produce a signal-to-clutter ratio of 1.0 (0.0 dB).

Area Clutter

The assumption is that most ground clutter will be seen at low-grazing angles (<1.0 degree) and, therefore, the backscattering area will be constrained by the azimuth beamwidth and the pulse width ($R\ \theta_a\ c\ \tau/2$). An average backscatter coefficient for a variety of terrains at low-grazing angles at 9 Gigahertz is assumed to be 0.01 (-20 dB) (ref 7). The backscatter areas of the three beamshapes in the presence of ground clutter will be the same and, at 12 km, these areas are calculated to be 29.0 dB.

The combined effects of operating in the presence of both rain and ground clutter would result in the addition of the returns from the rain and ground clutter in an rms manner. Calculating the combined backscatter returns for the three antenna configurations, one finds the clutter-to-noise ratios for combined clutter at 12 kilometers to be:

Single 30-degree elevation fan beam, 36.5 dB

Dual fan beam, 40.7 dB/beam

Single 6-degree elevation fan beam, 50.0 dB

The signal-to-clutter ratios for the three antenna configurations will then be:

Single 30-degree elevation fan beam, 29.4 dB

Dual fan beam, 29.0 dB/beam

Single 6-degree elevation fan beam, 29.0 dB

This indicates that the ground clutter predominates. No amount of clutter suppression will improve the signal-to-noise ratio; therefore, the maximum signal-to-clutter ratio (single hit) for the three antenna configurations is:

Single 30-degree elevation fan beam, 7.1 dB

Dual fan beam, 22.7 dB/beam

Single 6-degree elevation fan beam, 21.0 dB/beam

If a 40-dB signal-to-clutter improvement were achieved, the resulting single-hit signal-to-clutter ratios would be:

Single 30-degree elevation fan beam 7.1 dB

Dual fan beam, 11.0 dB/beam

Single 6-degree elevation fan beam, 11.0 dB

Both the single 30-degree elevation fan beam and the dual fan beam systems will require pulse integration to achieve a probability of detection of 0.90 because the clutter has been suppressed to the noise level. The single 6-degree elevation fan beam system will still provide a single-hit probability of detection of 0.90 since that clutter has only been suppressed to 10 dB above the noise level and the signal-to-clutter ratio is 11 dB. The signal-to-noise ratio remains at 21 dB.

The expectation is anticipated that the clutter will have a maximum spectral width of about 120 Hz (2.0 meter/second) (ref 8). To achieve a 40-dB signal-to-clutter improvement with a 120-Hz clutter spectral width and a PRF of 8 kHz will require a two-canceler MTI system (ref 9). (A two-canceler MTI system

will provide a 40-dB improvement for a clutter spectral width of 144 Hz and a 52-dB improvement for a clutter spectral width of 80 Hz, both at a PRF of 8 kHz).

The single 30-degree elevation fan beam system will see ground clutter on all scans. However, only the lower beam of the dual fan beam system and only the lowest scan of the single 6-degree elevation fan beam system will see most of the ground clutter.

Blind Speeds and Dynamic Range

Blind speeds occur where the doppler frequency is some integer multiple of the PRF. In the case of a system operating at 9 GH_2 at a PRF of 8 kHz, the blind speeds will occur at

$$\nu_{B\eta} = \frac{\eta \ \lambda \ PRF}{2} = \frac{\eta \times 0.033 \times 8000}{2} = 133.3;\ 266.7;\ 400.0 \text{ m/sec}$$

for η = 1, 2, and 3

Two blind speeds exist within the range of interest. These doppler ambiguities may be resolved by changing the PRF. (The PRF may only be lowered in order not to exceed the duty cycle of the transmitter tube). If the PRF were changed to 7407 Hz (accomplished by increasing the interpulse period from 125 microseconds to 135 microseconds), the blind speeds would become

124.4, 248.8, and 373.1 m/sec for η = 1, 2, and 3

If the PRF is staggered on a pulse-to-pulse basis, all speeds of interest can be resolved each time the antenna beam passes over the target. However, second-time-around clutter returns will not be canceled if pulse-to-pulse staggering is implemented. Therefore, groups of ten pulses should be staggered, i.e., ten pulses at one PRF and the next ten pulses at the second PRF , etc. Since 55 hits per point target are received with a 360 degrees/second scan rate, all speeds can be resolved in each scan, and second-time-around clutter returns will be canceled.

A 1-m^2 target will have a dynamic range of about 56 dB (12 kilometers to 500 meters) in a 4 mm/hr rainfall due to the range and rain attenuation decrease (≈55.2 dB due to range and 0.76 dB due to rain attenuation).

Area (ground) clutter will have a dynamic range of about 42.2 dB under the same conditions, whereas volume (rain) clutter will have a dynamic range of about 28.4 dB. Ground clutter variations in the order of 40 dB are likely to occur because of the scanning of the antenna through 360 degrees. This is especially true if point clutter is in the surveillance region. A linear-limiting IF amplifier can be used to make the residual ground clutter more noiselike and allow more effective moving target indicator (MTI) operation. (Limiting also tends to decrease the improvement factor obtainable with MTI, but the over-all results of limiting increase the moving target detectability in residual clutter). The expectation is that sensitivity time control (STC) will also be used in the receiver to suppress the transmitter pulse and close-range clutter.

Jamming

This report does not specifically address ECCM techniques to be used in a jamming environment. The antenna sidelobes were maintained at a low level to reduce the effects of clutter and stand-off jammers. The frequency agility provided with the transmitter tube (40-MHz instantaneous bandwidth with 1000-MHz tuning range) could be effective against spot frequency and repeater-type jammers but will require a sophisticated frequency synthesizer to take advantage of the frequency agility while maintaining coherence. Frequency agility at X-Band may also be restricted in a tactical situation due to required frequency allocations. Techniques other than frequency agility will be required for barrage-noise jamming.

Track Radar Designation and Handoff

The track radar will be designated from the search radar. Handoff will occur when the search radar declares a target of interest. A target of interest will be declared by the search radar when the output of the MTI system exceeds a threshold set at the level of the residual clutter.

Accuracy of Designation

The time required for the track radar system to acquire a designated target depends on the accuracy of the designated parameters.

The three approaches to the search radar system provide the same designation accuracy in range (150 m) and azimuth (2.5 degrees). The accuracy of elevation designation depends on the antenna system used.

The single 30-degree elevation fan beam system can only designate to 30 degrees in elevation (45 degrees if the cosecant^2 pattern is used). The dual fan beam system can designate to a ± 1 degree elevation between elevations of 7.5 degrees to 22.5 degrees and to a 7.5 degree elevation between elevations of 0.0 degrees to 7.5 degrees and 22.5 degrees to 30 degrees. The single 6-degree eleveation fan beam system can designate to a 6-degree elevation.

Beam-slicing techniques could be used to try to improve the azimuth-designation accuracy; but these would require additional equipment, and the improvement in designation accuracy would be limited. A cosecant^2 beam pattern cannot be effectively sliced in elevation. The single 6-degree fan beam could conceivably improve its elevation-designation accuracy by making scan-to-scan comparisons; but, again, this would require additional equipment with limited-elevation designation-accuracy improvement.

If the maximum elevation coverage is limited to 30 degrees, a 5-degree elevation beam could scan the 30 degrees in a 6-second time frame. This would improve the elevation-designation accuracy (over the 6-degree beam) while improving the antenna gain slightly (0.8 dB).

Recommendations

A tactical situation with a multiple target environment and the requirement of identification of hostile targets will necessitate a much more sophisticated system than this report

considers. In such a tactical situation as above, a track-while-scan capability will be required; this implies scanning a narrow beam over the complete search coverage. The scanning can only be accomplished in reasonable time frames with an electronic scan in elevation (the antenna system can be scanned mechanically in azimuth). The track-while-scan feature on a moving vehicle will necessitate a stable reference (either a stabilized antenna system or the antenna referenced to a stabilized platform) so that new detections may be cross-gated to see if the new detections represent new targets or stored targets. The fact that targets will be stored and updated suggests a computer-controlled search radar system. A threat analysis can then be performed, and the highest priority target can be designated to the track radar system.

The search radar system recommended in this report is very unsophisticated. The basic intent of the system is to achieve a probability of detection of 0.9 on a one meter^2 target at 12 kilometers in a clutter environment with the least amount of signal processing and to designate the track radar as accurately as possible.

The antenna will be scanned mechanically in elevation one 6-degree beamwidth for each 360-degree azimuth scan for a total of six consecutive azimuth scans. The antenna will then be snapped back to the starting point. Either a stepped elevation scan or a continuous (helical) elevation scan may be used, but care must be exercised not to leave any holes in the search coverage.

All calculations and assumptions are based on a fixed (relative to the earth) search radar system. Provisions will have to be made, especially in terms of clutter rejection, to mount the search radar system on a moving vehicle.

A comparison of the three antenna configurations considered is shown in table 3. Other antenna configurations can be considered; but, in general, they will require either increased frame times to achieve the required search coverage or electronic scanning techniques.

Table 3. Comparison of three antenna configurations

Antenna Configuration	Single-Hit Signal-to-Noise Ratio (4 mm/hr rain) 12 km Range	Track Radar Acquisition Time
Single fan beam; 2.5° azimuth, 30° elevation (45° CSC^2)	7.1 dB	11.0 seconds
Dual fan beam; 2.5° azimuth, 15° elevation (each beam)	11.7 dB	2.7 seconds
Single fan beam; 2.5° azimuth, 6° elevation (scanned in elevation)	21.0 dB	2.2 seconds

A simplified block diagram of the recommended search radar system is illustrated in figure 3. This block diagram shows only the basic blocks for the system. The stable local oscillator and the coherent oscillator frequencies may be derived from a frequency synthesizer. While analog techniques are shown for clutter rejection, the clutter rejection may be achieved with digital techniques.

TRACK RADAR DESIGN

Configurations

Track radar has historically been developed in conformance to one of three general configurations. These are conical scan, amplitude comparison monopulse, and phase comparison monopulse. Because of the desired system reaction time, a monopulse system

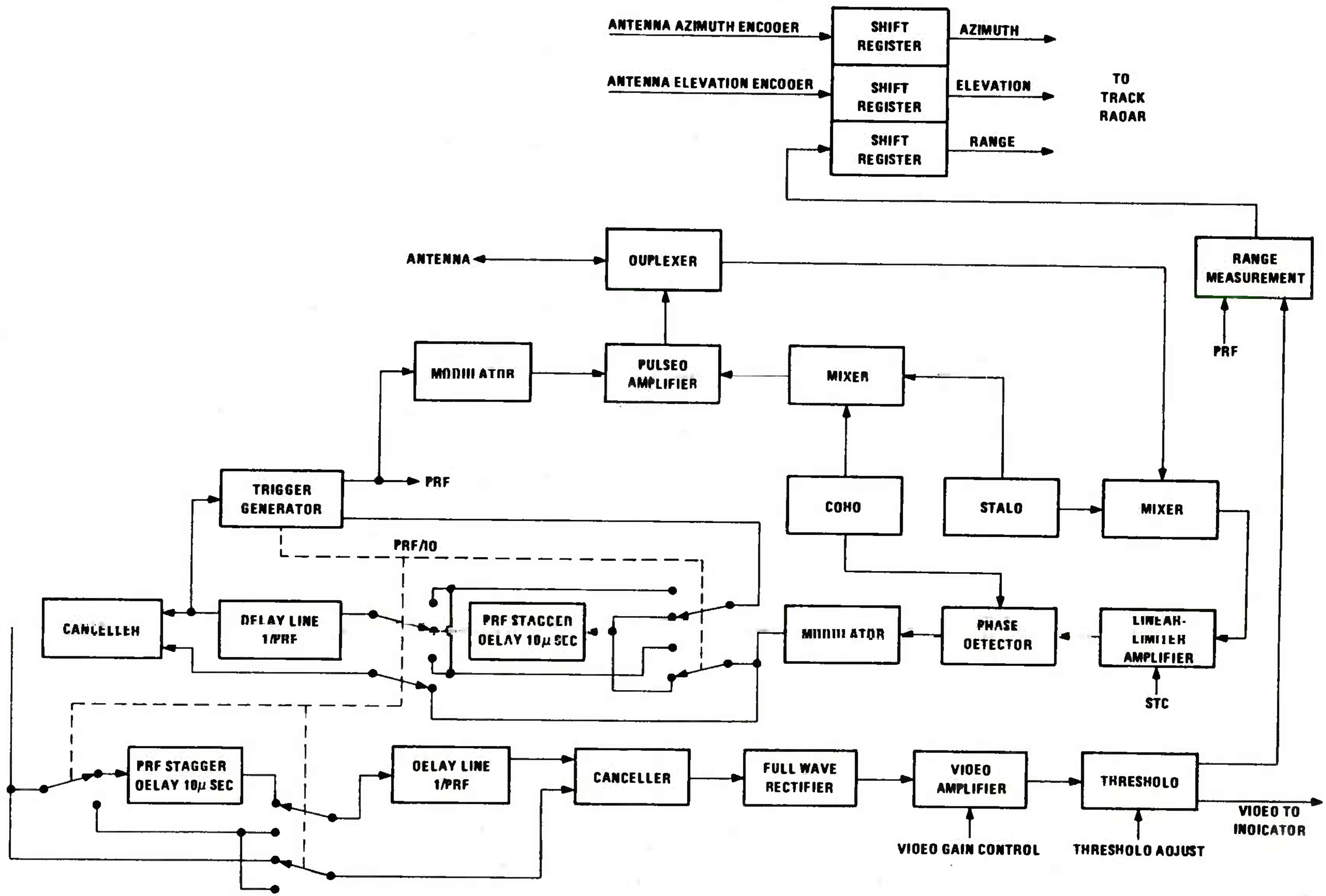

Figure 3. Block diagram of recommended search radar system.

is preferable to a conical scan. A monopulse system can track on a single hit, whereas four pulses are required to track on a conical scan system.

The phase comparison monopulse is not a desirable system because of the inefficient use of antenna aperture, the need for multiple antennas, and the accompanying high sidelobe levels.

Of the three general configurations, the amplitude comparison monopulse is the most desirable for millimeter wave applications. A block diagram of a typical two-coordinate amplitude-comparison monopulse track radar is shown in figure 4.

Acquisition Mode

Before lock-on, a track radar must operate in the same manner as a search radar before any of the tracking loops are closed. This presents a hardship on the track radar design since a good signal-to-noise ratio must be developed in the IF circuits to allow the servo loop to easily track the target once lock-on is achieved.

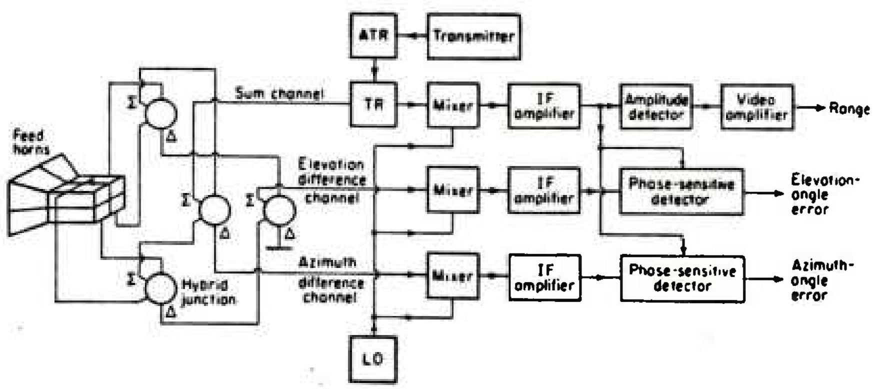

Figure 4. Typical block diagram for monopulse track radar.

Since the track radar is required to operate in an acquisition mode, the search area must be restricted to increase the number of "looks", or scans, at the target.

Track Radar Search Volume Analysis

Two search options for the acquisition mode of the track radar are considered for analysis. First, the track radar is supplied with range and azimuth data only. The second option addresses the case of the track radar receiving elevation data in addition to range and azimuth data.

For the purpose of this analysis, the range and azimuth inputs to the tracker will be considered first.

If the assumption is that the target appears initially to the search radar at 12 kilometers and if the designation time of the search radar is 5 seconds, a target traveling at Mach I will have progressed 1500 meters along a radial course. This is the worst case, for it means that the track radar will be attempting to acquire the target initially at 10.5 kilometers. Since the tracker is required to have a minimum acquisition range of 7.5 kilometers, the track radar must achieve acquisition in roughly 10 seconds.

The track radar is required to search a volume of space the size of which is dependent on the input data from the search radar. A typical volume is shown in figure 5. When no elevation data are present, the track radar must search the entire elevation beamwidth of the search radar.

To search this large an area, a raster scan for the acquisition mode is the most desirable. The raster scan can be optimized so that elevation angles of greatest importance have maximized dwell times. For the purpose of this analysis, which will show the differences in track performance due to the presence or absence of elevation data, all elevation angles are assumed to have the same importance.

A survey of available information on servo scan rates shows 13.8-degree/second servo speed in azimuth to be a

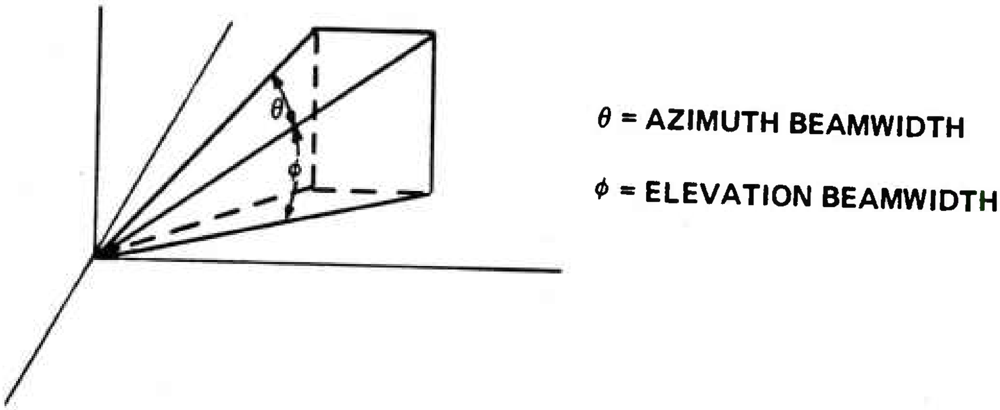

Figure 5. Search volume required for track radar.

typical value. With no elevation data, the search volume would be as shown in figure 6a (2 degree azimuth beamwidth was chosen as a typical value). With elevation data, based on the analysis in previous sections, the search volume is reduced to that shown in figure 6b, assuming a 0.5-degree x 0.5-degree track beamwidth. Given a 13.8-degree/second servo scan rate in azimuth, for the first case, A, shown in figure 6a, a minimum of 8.7 seconds is required to illuminate the entire volume. However, the second case, B, illustrated in figure 6b, requires a minimum of 1.7 seconds. Note that these scan times are used for illustration only and do not include stop times or vertical scan times that are assumed to be the same for both cases.

Since the track radar has approximately 10 seconds to acquire the target, case A allows just one look at the target, but case B allows five looks in the same time span. If the probability of detection on a single hit is given as 0.9, the cumulative probability of detection can be found from the following expression:

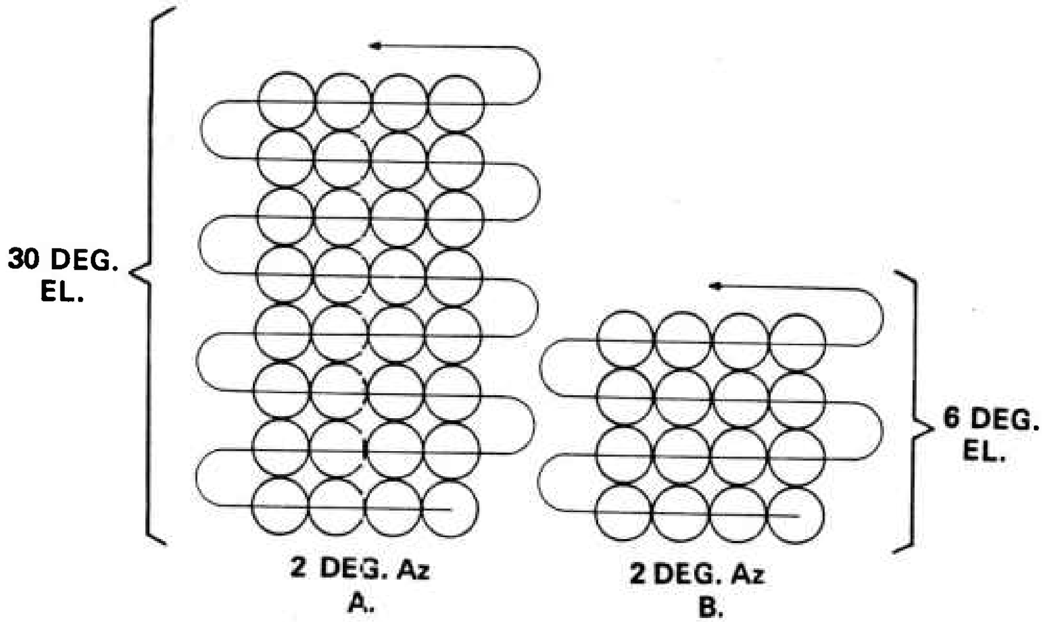

Figure 6. Search volume as a function of elevation data.

$$P_c = 1 - (1 - P_d)^j$$

where P_c = cumulative probability of detection

P_d = single hit probability of detection

j = number of looks, or scans

For case A,

$$P_c = 1 - (1 - 0.9)^1 = 0.9$$

For case B,

$$P_c = 1 - (1 - 0.9)^5 = 0.99999$$

Another way to observe the difference between the two cases is to calculate the single hit probability of detection given that a 0.9 cumulative probability of detection is desired. This yields a $P_d = 0.9$ for case A and a $P_d = 0.37$ for case B. Correspondingly, a reduction in required S/N results when case B is compared to case A, when a cumulative detection scheme is assumed.

From the perspective of the operational requirements, an 8.7-second scan time allows approximately 2.7 kilometers of target travel. In light of the distance traveled by the target, case A appears undesirable. If the target slips through the search volume undetected, the tracker is unlikely to lock-on. Given an appropriate target flight profile, the target could avoid detection in case B as well. This condition is discussed in a later subsection.

A final comparison of the two search volumes can be made in terms of the required power output. The difference between the power requirements for the two options is reflected in the relative S/N.

For both cases, the PRF selected 10,000 Hz. Since the dwell time in both cases is 0.036 seconds, the number of pulses exchanged is 360 per dwell.

As previously calculated, the single hit probability for case A was 0.9; whereas, for case B, it was 0.37. If P_{fa} is selected to be 10^{-6} in both cases, $(S/N)_1$ is 13.2 dB and 10 dB, respectively. However, when Swerling Case I is considered, $(S/N)_1$ for case increas es to 21.2 dB. If 360 pulses are coherently integrated in both cases, the relative (S/N) for case A becomes -4.4 dB; whereas, for case B, (S/N) becomes -15.6 dB. This result indicates an 11.2 dB reduction in required output power. If the pulses were integrated noncoherently, the relative (S/N) for case A would be 4 dB with approximately 6 dB of integration loss. For case B, the relative (S/N) is roughly -4 dB, with approximately 8 dB of integration loss. The improvement in reduced required power for case B over case A is approximately 6 dB for noncoherent integration.

When all factors suxh as system reaction time, required output power, and cumulative probability of detection are considered, elevation data should be supplied to the track radar. The estimation is that these data would increase the system complexity by approximately 10 percent.

Given the additional constraints on performance such as rain and ground clutter, a substantial S/N ratio is required to drive the servo loop. Thus, to scan the target several times before acquisition is advantageous. For this reason, the design of the 94 GHz tracker will be based on the assumption of having elevation data available.

System Analysis in the Acquisition Mode

The requirements for the track radar are repeated below for convenience.

Frequency	94 GHz
Acquisition range (minimum)	7.5 kilometers
Track accuracy	1 milliradian rms
Range resolution	75 meters
Target velocity	0-310 meters/second
Target altitude	6-6000 meters
Rain rate	4 millimeters/hour
Target cross section	1 meter^2, Swerling Case I

A survey of existing technology reveals that a typical peak power output and duty cycle are one kW peak and one percent. These data come from the specification sheet of the HAW-7 Traveling Wave Tube manufactured by Hughes Research Laboratory.

In the previous discussion, the target was shown to initially appear to the track radar at approximately 10.5 kilo-

meters on the assumption that the search radar requires 5 seconds to designate the target. Consequently, the PRF should be selected for an appropriate unambiguous range. This can be determined as follows:

$$R_u = \frac{c}{2\ f_r} \text{ or } f_r = \frac{c}{2\ R_u}$$

where c = 3×10^8 m/sec

R_u = unambiguous range

f_r = pulse repetition frequency

If R_u is chosen to be 11 kilometers, then f_r = 13.636 Hz. This represents an upper limit to the PRF. For the purpose of this design, f_r is chosen to be 10 kHz. This selection is made to reduce the duty cycle and allow pulse-to-pulse staggering. Since $B\ \tau = 1$, a 0.5-second pulse width will yield an IF bandwidth of 2 MHz. Further, the duty cycle becomes $\tau\ f_r = (.5 \times 10^{-6})\ (10^4) = 0.005$.

The track radar beam pattern is chosen to be 0.5 degrees x 0.5 degrees to ensure meeting the track accuracy requirement and to reduce ground and rain clutter.

The selection of 0.5 degree as the beamwidth was made as a result of a trade-off between higher required scan rates in the case of a narrower beam versus enhanced ground and rain clutter in the case of a wider beam.

Analysis in the search radar section resulted in a recommendation to provide to the track radar a search uncertainty volume 2.5 degrees wide in azimuth and 6 degrees wide in elevation with 6 seconds between search radar updates. Given the search volume and a scan rate of 13.8 degrees/second in azimuth, the volume could be scanned in a minimum time of 2.2 seconds. This provides nearly three looks or scans between search radar updates. Given a slight increase in scan rate, three full looks can be achieved within 6 seconds. To achieve a cumulative probability of detection of 0.9, the single scan P_d can be determined by the expression:

$$P_d = 1 - (1 - Pc)^{1/j}$$

where P_d = probability of detection per scan

P_c = cumulative probability of detection

j = number of scans

$$P_d = 1 - (1 - 0.9)^{1/3} = 0.536$$

For a $P_{fa} = 10^{-6}$ and $P_d = 0.536$, the $(S/N)_1$ required is 13 dB.

To determine the amount of integration gain required, one must apply the radar range equation

$$\frac{S}{N} = \frac{\hat{P}\ G^2\ \lambda^2 \sigma}{R^4\ (4\ \pi)^3\ KT\ B\ (NF)\ L_s}$$

where,

S/N = input signal-to-noise ratio prior to integration

$\hat{P}$ = peak power of the transmitter

λ = operating frequency wavelength

σ = radar cross section

KT = thermal noise power/Hz

B = IF bandwidth

L_s = system losses

G = antenna gain

NF = noise figure

$\hat{P}$, as discussed earlier, was chosen to be one kW; λ is determined by c/f and is equal to 3.19×10^{-3} meters; σ was defined to be one meter^2. The thermal noise power is equivalent

to -204 dBW, and the IF bandwidth was determined earlier to be 2 MHz. The antenna gain may be found from the following expression:

$$G - \frac{41,253}{\theta\phi}$$

where θ = azimuth beamwidth in degrees

ϕ = elevation beamwidth in degrees

$$G = \frac{41,253}{(0.5)\ (0.5)} = 165,012$$

However, antenna efficiency, which is chosen to be 0.6, must be taken into account. Therefore,

$$G_e = \rho\ G = (0.6)\ (165,012) = 99,007$$

Given the efficiency and beamwidth, the aperture size for a $\cos^2$ illumination distribution can be found from

$$a = \frac{91\lambda}{\theta}$$

where a = aperture width

λ = wavelength

θ = beamwidth

$$a = \frac{91\ (3.19 \times 10^{-3})}{0.5} = 0.58\ \text{m.}$$

The system losses are comprised of scan/scan fluctuation loss, beam shape loss, atmospheric absorption, hybrid, waveguide, and constant false alarm rate (CFAR). The values for these losses were derived through a survey of the available literature and references. The values found are listed below:

Loss	dB
Scan/scan fluctuation	0.5
Beam shape	3.2
Hybrid	6.0 (2 hybrids, two way path)
Waveguide	2.0 (95 dB/100 ft)
Absorption	5.6 (0.37 dB/km one way)
CFAR	1.5
TOTAL	18.8

The noise-figure value was determined by a survey of available technology. A Hughes mixer/preamp at 94 GHz was found to have a 12 dB noise figure. This unit turned out to be typical for this frequency.

As a result of the above values, the S/N prior to integration can be determined as follows:

$$S/N = \frac{\hat{P}\ G^2\ \lambda^2\ \sigma}{R^4\ (4\pi)^3\ KT\ B\ (NF)\ L_s}$$

	+dB	-dB
$\hat{P}$ (1 kW)	30	
G^2	100	
λ^2		50
R^4 (7.5 km)	0	
$(4\pi)^3$		155
KT		33

B		63
NF		12
L_s		18.8
	334.0	331.8
	331.8	
S/N =	2.2 dB	

Required integration gain in acquisition is 13 dB - 2.2 dB = 10.8 dB. The required integration gain is determined by consideration of the required single hit S/N based on a probability of detection of 0.54. This P_d is derived from the following expression:

$$P_c = 1 - (1 - P_d)^j$$

where P_c = cumulative probability = 0.9

j = number of "looks" = 3

Note that the required single hit S/N for one look at a Swerling Case I target is 22 dB for a probability of false alarm of 10^{-6}. The above expression requires one detection in three looks at the lower threshold level (13 dB). The price paid when the threshold is lowered from 22 dB to 13 dB is the false alarm rate. To achieve the false alarm probability of 10^{-6} at the 22 dB level, one must reduce the false alarm rate at 13 dB to approximately 3×10^{-6}. This result implies an increase in integration gain above the minimum to improve the S/N and to reduce the severity of the necessary false alarm rate.

Other factors such as weather also require a higher integration gain to achieve minimum performance.

The case of fog will be addressed first. From the available data of previous studies, attenuation due to fog has been determined to be 0.5 dB/kilometer at 0 degree C with a liquid water content of 0.1 gram/meter^3. At a range of 7.5 kilometers, fog will provide an additional 7.5 dB of attenuation.

The most damaging hindrance to performance however is rain. At a 4mm/hr rain rate, the attenuation at 94 GHz is 3.4 dB/kilometers one way. At a range of 7.5 kilometers, the attenuation would be 51 dB. This rain condition virtually puts any effective operation at 94 GHz out of reach for a detection range of 7.5 kilometers. Another way to observe the impact of 4mm/hr of rain is the reduction in detection range if other conditions remain the same. The resultant detection range drops to roughly 1.8 kilometers with no integration gain. Two options are available under this condition. One option is to add a track capability to the search radar. Another option is to maximize the performance in 4 mm/hr of rain.

No data were available on smoke attenuation; therefore, no calculations were made for this condition.

For the same integration gain, the major differences in performance between the two systems (coherent versus noncoherent) are the integration time and the ability to directly measure the doppler frequency return. The coherent integration time for the same gain will be significantly less than the noncoherent case. Further, the doppler frequency cannot be directly measured in a noncoherent system since the IF phase is not correlated with the transmitter-oscillator phase. The shorter integration time and the capacity to measure the doppler frequency allow the coherent system to be more flexible and to permit the system to retain the potential of varying integration time to achieve a burn-through mode while doppler frequency is still being measured.

With the future of technology at 94 GHz and the superior performance of a coherent system kept in mind, the development of a coherent system is recommended. The design presented in this section is for a proposed coherent system.

Clutter Effects

The clutter sources to be considered are ground, rain, and fog. From previous studies, the backscatter from fog has been found to be negligible at 94 GHz.

For the case of rain, previous studies have shown that severe attenuation results from absorption at 4 mm/hr. Thus, the expectation is that the proposed system configuration,

which is discussed in greater detail in succeeding subsections, will have a burn-through mode and an adaptive threshold. When excessive interference, such as that caused by rain, is present, the integration gain will be increased to a maximum value consistent with beam-position dwell time and signal processing time. The maximum integration gain that is feasible has been determined to be roughly 23 dB. The effect on S/N as a function of 4 mm/hr of rain at various ranges is shown in figure 7. Note that the detection range at the burn-through gain level is nearly 3.7 kilometers. This will be the range at which the rain clutter is computed.

The backscatter coefficient for 4 mm/hr of rain at 94 GHz has been determined from previous studies to be 1.9 x 10^{-4} m^2/m^3. The equivalent cross section may be found from the expression below:

$$\sigma_r = R^2 \theta^2 \left(\frac{c\tau}{2} \eta \right)$$

where,

σ_r = radar cross section of rain

R = detection range - 3.7 km

θ = beamwidth (radians) = 8.73×10^{-3}

c = 3×10^8 m/sec

τ = pulse width = 0.5 usec.

η = backscatter coefficient = 1.9×10^{-4}

$\sigma_r = (3.7 \times 10^3)^2 (8.73 \times 10^{-3})^2 (75) (1.9 \times 10^{-4})$

$\sigma_r = 14.9 \text{ m}^2$

The clutter rejection required for rain is a minimum of 11.7 dB to bring the ratio of the rain cross section to the target cross section to one.

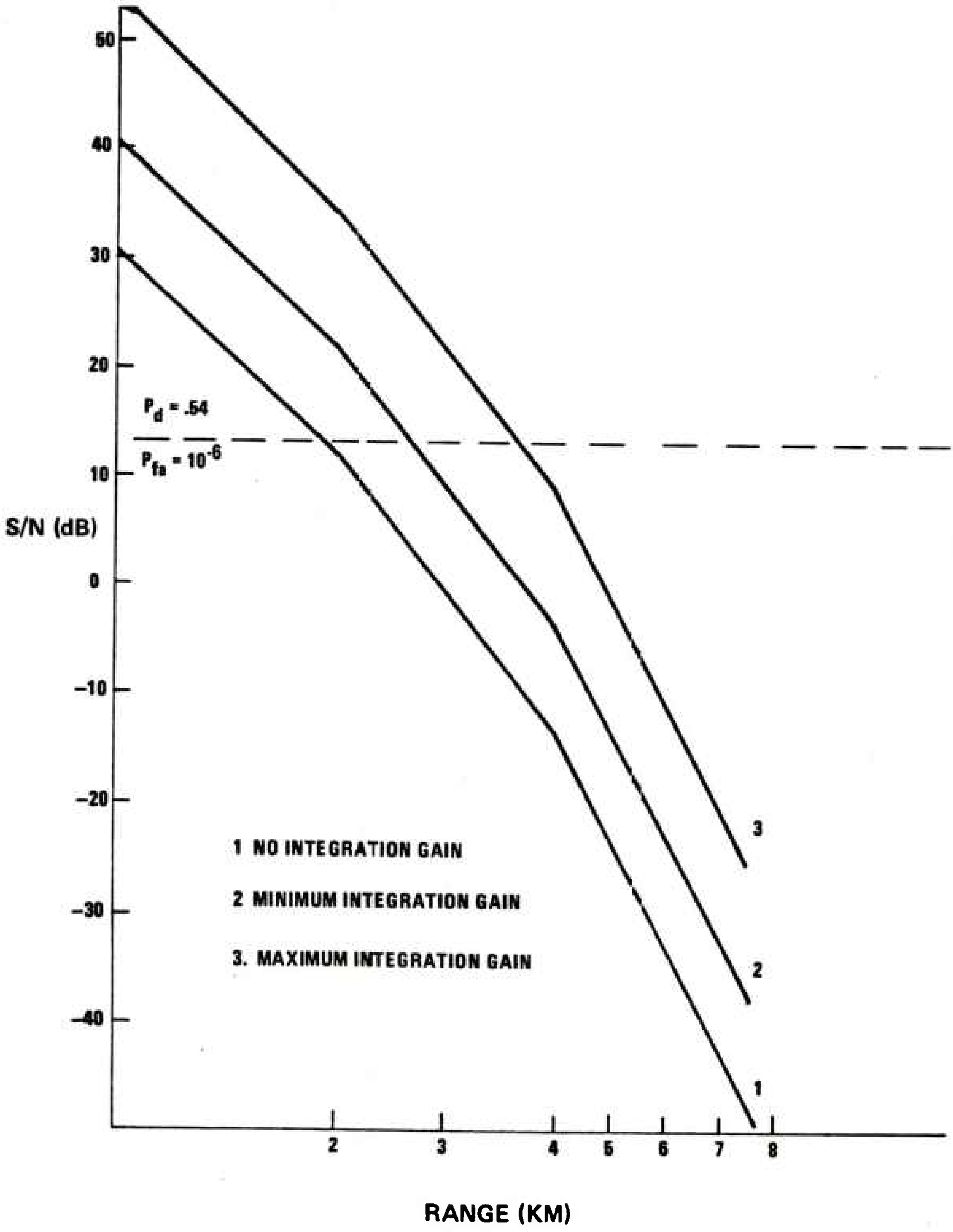

Figure 7. Impact on S/N versus range with 4 mm/hour of rain.

For ground clutter, the worst case occurs at the desired detection range of 7.5 kilometers at low-grazing angles. A survey of the references indicated that an approximate backscatter coefficient for ground clutter at 94 GHz is -20 dB (meter)^2. At low-grazing angles, the equivalent radar cross section for clutter can be found from the equation:

$$\sigma_g = R\,\theta \left(\frac{c\,\tau}{2}\right) \sigma^o$$

where,

σ_g = ground-clutter radar cross section

R = radar range

c = 3×10^8 m/sec

τ = pulse width = 0.5 usec

σ^o = ground-clutter backscatter coefficient

θ = beamwidth (radians) = 8.73×10^{-3}

$$\sigma_g = (7.5 \times 10^3)\,(8.73 \times 10^{-3})\,(75)\,(0.01) = 49\ m^2$$

The resultant ground clutter cross section corresponds to a required clutter rejection of roughly 17 dB.

The worst case, when both ground clutter and rain clutter would occur, is at 3.7 kilometers. At 3.7 kilometers, the ground clutter cross section is 24.2 meter^2. The rms cross section of both ground and rain clutter is 28.4 meter^2, corresponding to a clutter-rejection requirement of 14.5 dB.

From the results calculated above, the worst case is the ground clutter at 7.5 kilometers. Consequently, the clutter rejection performance of 20 dB is selected to achieve at least 2.2 dB S/N.

From the references, the approximate bandwidth at the half-power points of the clutter spectrum is approximately 200 Hz.

The method recommended to reject the clutter spectrum is the clutter rejection filter. A filter is used to avoid the restriction of the dynamic range of the system. This also readily allows the addition of ECCM techniques later on in the system development.

During normal operation, the clutter will be rejected by a filter bank that will have a bandwidth approximately as wide as the PRF. To achieve the desired cumulative probability of detection, the use of a nominal coherent integration gain of 20 dB is required. This results in a filter bank in which each filter will have a 100 Hz 3 dB bandwidth. To achieve a 20-dB clutter rejection at 200 Hz and at f_r - 200 Hz requires that the filter bank will have an overall bandwidth of 9200 Hz. Each filter will exhibit the characteristics of a three-pole maximally flat delay filter. The frequency spectrum will appear as shown in figure 8 for one filter.

To cover 9200 Hz, such a filter bank would have to consist of 92 filters, each with a 100-Hz bandwidth. To implement such a configuration with an analog system would be cumbersome, to say the least. A digital system is far more practical and has the advantage of flexibility in readily changing number of filters and their bandwidths. In addition, future changes in system requirements will have minimal impact on a digital configuration. The filter bank will serve two purposes, for it will not only reject the clutter, but will also provide the required integration gain.

The implementation of the digital filter bank is discussed in subsequent subsections.

Blind Speeds

The doppler bandwidth is determined by the following equation:

$$f_d = \frac{2\nu}{\lambda}$$

where,

f_d = doppler frequency

ν = target velocity

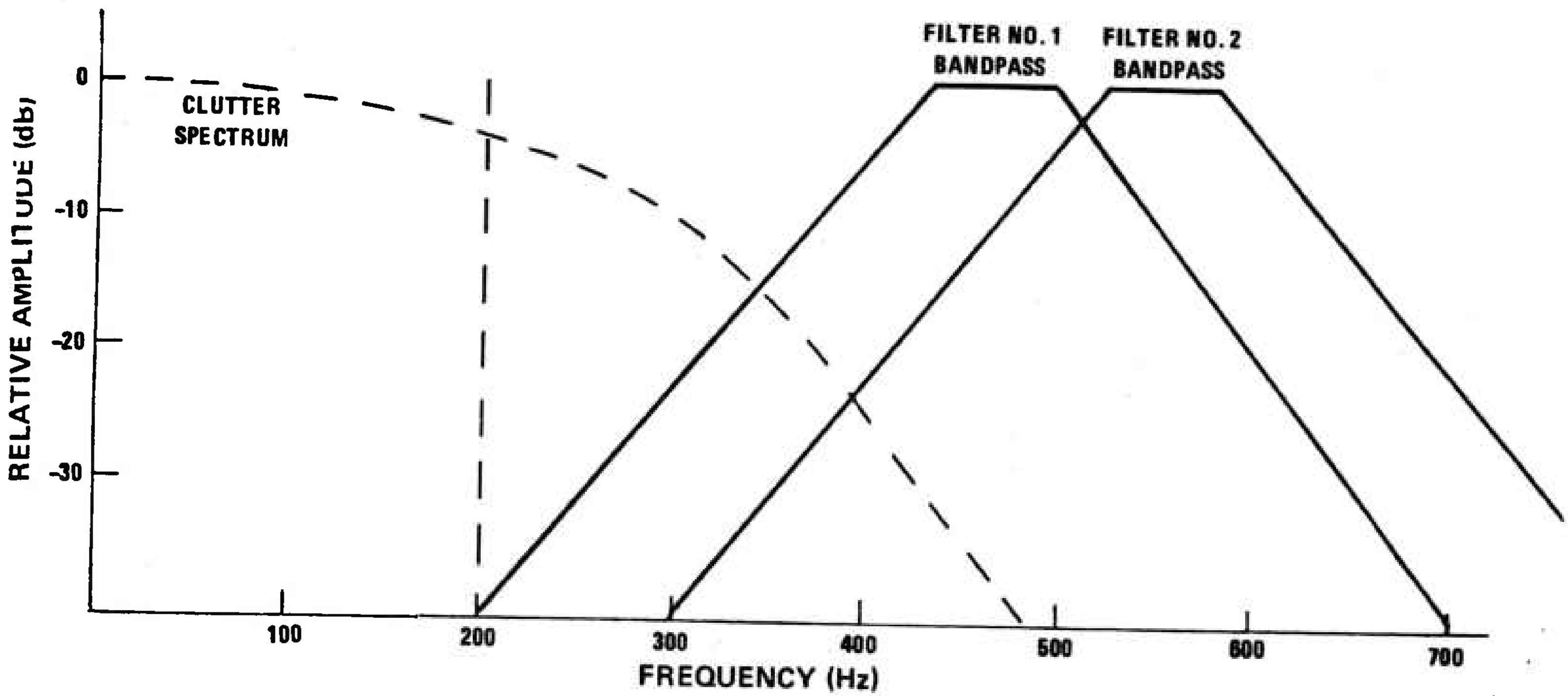

Figure 8. Frequency spectrum in the vicinity of the first filter in the filter bank.

λ = wavelength of transmission

$$f_d = \frac{2(310 \text{ m/sec})}{3.19 \times 10^{-3}} = 194.4 \text{ kHz}$$

Blind speeds occur at the PRF and at each of its harmonics. Within the doppler frequency range of interest, a 10 kHz PRF will produce 19 blind speeds.

At least two ways are available to deal with the blind speeds. The PRF may be jittered from pulse to pulse or from scan to scan. Eventually, however, the track radar must lock on to the target, which implies a continual scan condition. The PRF could be staggered at some given time interval. During this time interval, however, the blind speeds would still exist. During track, this condition is undesirable. On this basis, the pulse-to-pulse stagger seems to be the most viable option.

The issue to resolve at this point is the number of PRF's to be jittered. To eliminate all blind speeds, note that the optimum number of PRF's to be jittered is four. Assuming that it is desired to have the first blind speed occur at 24 $\bar{f}_r$, the best ratio to use is 27:22:25:21. This ratio is in proportion with respect to 10 kHz, with 25 taken as the reference. This yields PRF's of 10,800:8800:10,000:8400. The average PRF ($\bar{f}_r$) becomes 9500 Hz, which causes the first blind speed to occur at 228 kHz. This is beyond 194 kHz, the maximum doppler frequency of interest.

The PRF jittering causes a change in the duty cycle. With the jittering described above, the average duty cycle becomes 0.0048. Further, the average number of pulses integrated drops from 40 to 38, which reduces the integration gain by 0.2 dB.

The major disadvantage of pulse-to-pulse jittering is the additional complexity required in the radar system. However, such complexity is a price that must be paid to elimi-

nate all velocities in which the target may hide. The impact of the PRF jittering in terms of components is reflected in the addition of at least two tapped delay lines with associated timing and trigger circuits.

Another possible approach would be to change the PRF whenever a target doppler disappears. The disadvantage of this approach is that if the switching time is too great, the radar may lose lock on the target.

The effect in the frequency spectrum of PRF jittering and on some given blind speed at a 10 kHz PRF is shown in figure 9. Note that, as the PRF is changed, the doppler frequency shifts its location in the doppler filter passband. Observe that the actual doppler frequency of the blind speed cannot be determined from the output of the filter bank. Doppler tracking circuitry is required to determine the actual doppler frequency.

Dynamic Range

The required dynamic range of the receiver can be determined from the equation:

$$S = \frac{\hat{P}\, G^2\, \lambda^2\, \sigma}{(4\pi)^3\, R^4\, L_s}$$

where,

S = received signal power at the receiver

P = peak power transmitted = 1 kW

λ^2 = transmission wavelength $(m)^2$ = 1.02×10^{-5}

σ = target cross section = 1 m^2

R = radar range = 7.5 km

L_s = system losses = 18.8 dB

G^2 = antenna gain = 100 dB

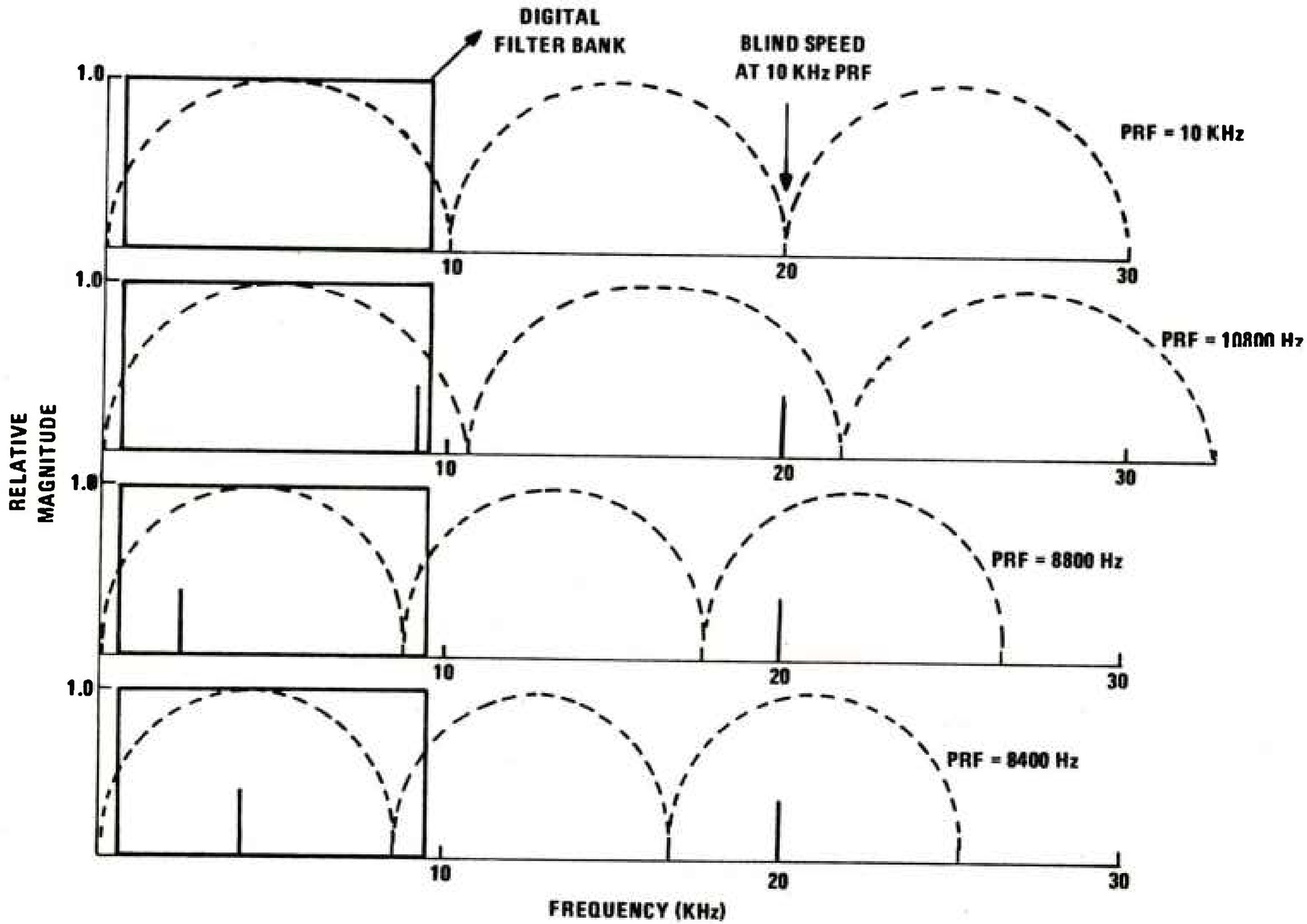

Figure 9. Blind speed with PRF jittering.

	+dB	-dB
P	30	
G^2	100	
λ^2		50
σ	0	
R^4		155
L_s		18.8
$(4\pi)^3$		33
	130	256.8
	- 256.8	

S = -126.8 dBw at 7.5 km

At the minimum range of 200 meters, S = -63.8 dBw, yielding a minimum dynamic range requirement of 63 dB. The received noise power can be determined from $N = KTB_{IF}$ = (-204) + (63) = -141 dBw.

To accommodate the adaptive threshold in the proposed system, note that the dynamic range required should be greater than the minimum. A major factor in determining the increase is the effect of a stand-off jammer on the received power.

As mentioned previously, the aperture distribution of the antenna is recommended to be $\cos^2$. This distribution, along with an efficiency of 0.6, will provide sidelobes at roughly -36 dB. Taking into account the effect of a Cassagrain configuration of the antenna, note that, if the subreflector is allowed to be approximately 0.1 the size of the main reflector, the sidelobes increase approximately three dB and the antenna gain is reduced by 0.3 dB due to aperture blockage.

A stand-off jammer at 100 kilometers must contend with only one way attenuation. Assuming that the same

peak power is radiated and that the signal comes through the sidelobe of the antenna, note that the power of the jamming signal at the antenna terminals would be:

$$P_J = \frac{\hat{P}\, G_J\, G_R\, \lambda^2}{(4\pi)^2\, R^2\, L_{AJ}}$$

where,

P_J = received power from the jammer

P_J = peak power radiated by the jammer

G_J = gain of the jammer antenna

G_R = gain of the radar antenna

λ = wavelength

R_J = range of the jammer from the radar

L_{AJ} = absorption loss from the jammer to the radar

The received power from the target at the same point (the antenna terminals) is expressed by the following equation:

$$P_r = \frac{\hat{P}\, G^2\, \lambda^2\, \sigma}{(4\pi)^3\, R^4\, L_{AR}}$$

where,

P_r = power received from the target

$\hat{P}$ = peak power radiated

G = radar antenna gain (main lobe)

λ = wavelength

σ = target cross section

R = range of the target from the radar

L_{AR} = absorption loss (two-way path) between the radar and the target

Keeping in mind the assumption made above concerning antenna gains and radiated power, note that a ratio of received target power to received jammer power can be derived. This ratio is expressed by the following equation:

$$\frac{P_r}{P_J} = \frac{G^2 \sigma R_J^2 L_{AJ}}{4\pi R^4 L_{AR} G_J G_R}$$

With the jammer at 100 kilometers radiating one kW peak power into the sidelobe of the antenna, the ratio can be determined.

	+dB	-dB
G^2	100	
σ	0	
R_J^2 (100 km)	100	
L_{AJ}	37	
4π		11
R^4 (7.5 km)		155
L_{AR}		5.6
G_J		50

G_R	$\underline{}$ 237	$\underline{17^*}$ 238.6
	$\underline{238.6}$	
$\frac{P_r}{P_J}$ =	-1.6 dBw	

This indicates that under the above conditions the desired signal is 1.6 below the jamming signal. When the range to the jammer decreases to 50 kilometers, $\frac{P_r}{P_J}$ becomes -26.1 dB. However, the jammer antenna is unlikely to have 50 dB gain; consequently, these computed ratios are pessimistic. Because of the need to allow for the possibility of jamming and for consideration of a jammer-antenna gain on the order of 30 dB, the additional dynamic range required for the AGC loop would be in the area of 6 to 7 dB, for a total of approximately 70 dB.

Acquisition Mode Operation Description

The acquisition of the target will be performed in the sum or reference channel of the track radar. A block diagram of the acquisition system is given in figure 10.

The designation data from the search radar triggers the acquisition process. The azimuth and elevation signals drive the track servo to the desired position; and the search-range word enters the range gate generator, which consists of a digital counter and a comparator. When the clock word is equal to the search-range word, the search-range gate is triggered. The width of the range gate is sufficient to allow 2.2 seconds of target travel either directly toward or away from the radar. In this case, the range gate is activated for a range interval $\pm$ 1 kilometer around the search-word designation. The range gate triggers the first LO that allows the IF signal to be generated as long as the range gate is present.

*GR = radar antenna gain, sidelobe loss = 50 dB, 33 dB = 17 dB.

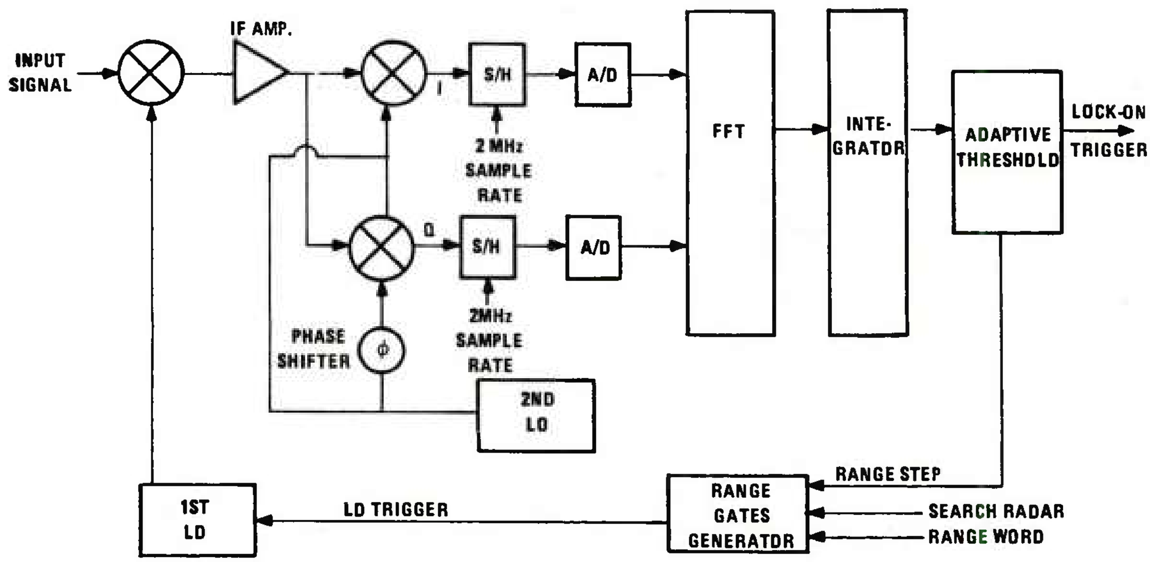

Figure 10 Block diagram of the acquisition system.

The IF signal is converted down by the second LO into the I and Q channels. The I and Q channels are required for the digital conversion that follows.

The sample and hold circuit commutates the analog signal for conversion by the A/D converter. The A/D converter generates a digital word from every 0.5 usec sample of the analog signal. The sample and hold retains the succeeding sample until the previous sample has been accepted by the FFT.

The FFT computes the frequencies of all the incoming samples. Depending on the constants used in the FFT, the effective bandwidth and computation time are determined.

A typical maximum computation time for the FFT is assumed to be 10 msec. The FFT, with its computation of frequency and the integrator, serves as the digital filter bank mentioned previously.

The integrator accepts the frequencies computed by the FFT, sums the samples present at each frequency, and computes the average. The magnitude that results at each frequency is applied to the adaptive threshold to determine **if a target exists**. If the threshold is exceeded, the adaptive threshold detector generates a lock-on signal that closes the range, aximuth, elevation, and doppler tracking circuits. If the threshold is not crossed, the track antenna is stepped to the next beam position. After all the beam positions in the search volume have been scanned, adaptive threshold circuit supplies a trigger signal to the range-gate generator to step the center of the range search window downward by 1 kilometer. This ensures three successive looks at a possible target traveling on a radial closing course at Mach 1. One detection in three looks at the target will achieve a 0.9 probability of detection.

After three looks, the acquisition system is updated by the search radar.

Note that in the acquisition mode the adaptive threshold circuit performs detection, decision, and triggering functions. In the track mode, it performs additional tasks such as threshold variation and AGC control.

Once the target has been acquired and the tracking loops are closed, a different set of systems conditions are present. These are described in the succeeding section.

Track Mode

Once the radar is locked on the target, the most important considerations are track accuracy and servo-system characteristics. However, the track mode is still constrained to a great extent by the parameters determined for the acquisition mode. As a result, the track and acquisition modes must be carefully integrated. For example, the pulse-to-pulse jittering must be present in the track system as well as in the acquisition system. The control of the AGC circuit in the

track system is a function of both the range tracker and the adaptive threshold. The integration gain must still be present in the track system to ensure a strong S/N for the servo loop.

Track Mode Analysis

The range equation in the track mode is significantly different from the acquisition equation because of the servo bandwidth. The tracking range equation is shown below:

$$R^4 = \frac{\hat{P}\ G^2\ \lambda^2\ \sigma}{(S/N)\ (4\pi)^3\ KT\ (B\beta)^{1/2}\ (NF)\ L_s}$$

where all quantities are the same as previously given except for the effective bandwidth. For this case, B = 2 MHz and β (servo bandwidth) = 10 Hz. The tracking range thus becomes,

	+dB	-dB
$\hat{P}$ (1 kW)	30	
G^2	100	
λ^2		50
(S/N)		2.2
$(4\pi)^3$		33
KT	204	
$\{\beta B\}^{1/2}$		36.5
NF		12
L_s		18.8
	334	

$$R^4 = \frac{152.5}{181.5}\ \text{dB}$$

$$R = 45.375 = 34.5\ \text{km}$$

The above value for the tracking range is deceptive since a S/N ratio below approximately four dB will usually prevent the servo loop from achieving lock on. Therefore, integration gain is required. If the minimum integration gain of 10.8 dB is added to the S/N, the tracking range drops to 18.5 kilometers. If the burn-through gain is added to the S/N, the tracking range is reduced to 9 kilometers.

With the minimum integration gain to achieve the desired S/N ratio to the servo loop of 13 dB, the track accuracy can be determined from the following expression:

$$\sigma_e = \frac{\theta B}{K_m \left(B\,\tau (S/N)\,(fr/\beta)\right)^{1/2}}$$

where,

θ_e = angular accuracy in radians (rms)

K_m = angle error detector slope = 1.57

B = IF bandwidth (Hz) = 2 MHz

S/N = signal-to-noise ratio

fr = PRF = 10 kHz

β = servo bandwidth = 10 Hz

θ = Beamwidth (radians) = 8.73×10^{-3}

τ = pulse width = 0.5 usec

$$\sigma_e = \frac{8.73 \times 10^{-3}}{1.57 \left[\{20(\frac{10^4}{10})\}\right]^{1/2}} = \frac{8.73 \times 10^{-3}}{1.57\ (141)}$$

$$\sigma = 3.93 \times 10^{-5} \text{ rad} = 39.3 \text{ microradians rms}$$

Attenuation due to weather

The tracking mode is subject to the same amount of degradation as the acquisition mode. Because the antenna is always on the target, the tracking range in rain is greater than the acquisition range. This leads to the conclusion that if the target can be acquired in rain, it can be tracked as well. The reduction in tracking range in 4 mm/hr of rain is shown in figure 11.

Clutter Considerations

Rain will produce clutter from backscattering in track as well as acquisition. Prior to pulse integration, this S/N ratio is relatively low and rain clutter has a strong effect. The same amount of rain clutter rejection is required in track as in acquisition.

For low-flying targets, ground clutter presents the same problem in track as in acquisition. Although the target is always in the track-beam volume, at low altitudes ground scatterers are present as well. To ensure sufficient ground clutter rejection it is required that the track channels have at least as much ground clutter rejection as the acquisition channel.

Dynamic Range

The acquisition dynamic range determined earlier is the same as the track dynamic range. However, the dynami c range is controlled by the AGC circuit in the track system.

Since the AGS must control the gain of the IF signal, it should have a bandwidth at least twice that of the IF. In this case, a minimum bandwidth of 4 MHz would be appropriate. In addition, it must produce a constant gain over a minimum of 63-dB dynamic range and should be capable of operation up to a maximum of 70 dB. Further, the AGC control is limited by the input S/N ratio. If the S/N is <4 dB, the track accuracy suffers from the predicted value calculated earlier.

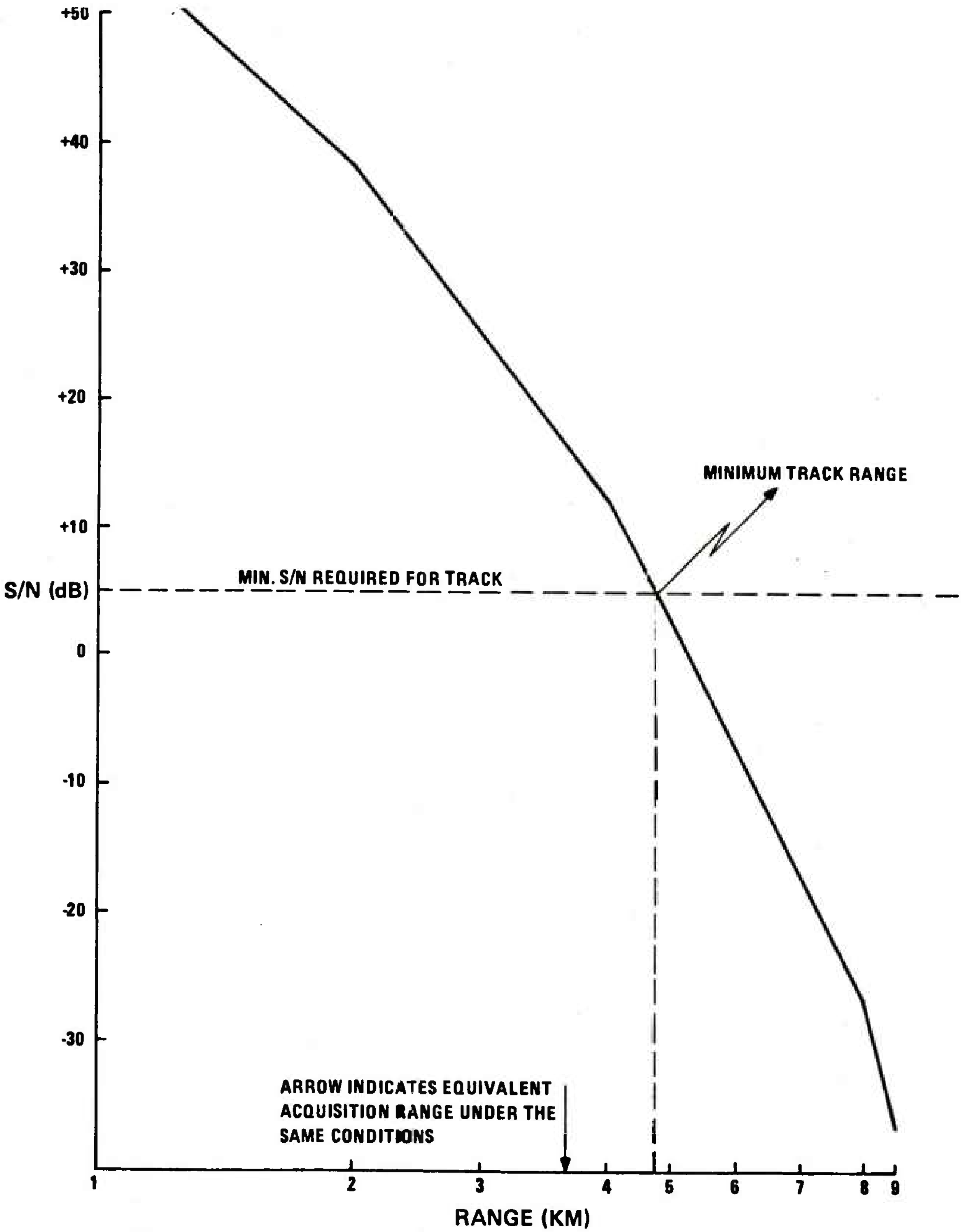

Figure 11. Impact on tracking range in 4 mm/hr of rain.

However, if the assumption is that the target is acquired at 7.5 kilometers, the S/N will increase above the 4 dB level by the time the target has reached 6.5 kilometers. Consequently, after roughly 3 seconds of track, the track accuracy is 0.1 milliradian rms.

Blind Speeds

The blind speeds determined earlier are present during the track mode as well if no system modifications are made. Earlier, PRF jittering was recommended to eliminate blind speeds during acquisition; the elimination of blind speeds is equally important during track as it is during acquisition.

Since the target is "searchlighted" during track, scan-to-scan PRF jittering seems to be a suspect option. Pulse-to-pulse staggering appears to offer more flexibility in dropping blind speeds although it adds to system complexity.

Track Mode Description

The block diagram of the track receiver without the pulse staggering circuitry is shown in figure 12. After the track radar has completed the acquisition mode and the lock-on trigger is generated by the adaptive threshold, the AGC circuit is activated and the range tracker receives its initial input.

When the range tracker receives the input digital word, the early range gate, which is one kilometer wide, is activated. When the early gate closes, the late gate is activated. The late gate is also one kilometer wide. The outputs of the early and late gates are subtracted to yield the range-error signal. At acquisition, the lock-on trigger from the adaptive threshold circuit switches range-gate control from the adaptive threshold circuit to the range tracker. The range tracker also senses the polarity and magnitude of the range error and uses this information to predict the target range. The video magnitude is sensed by the range tracker to produce a control voltage to adjust the AGC gain.

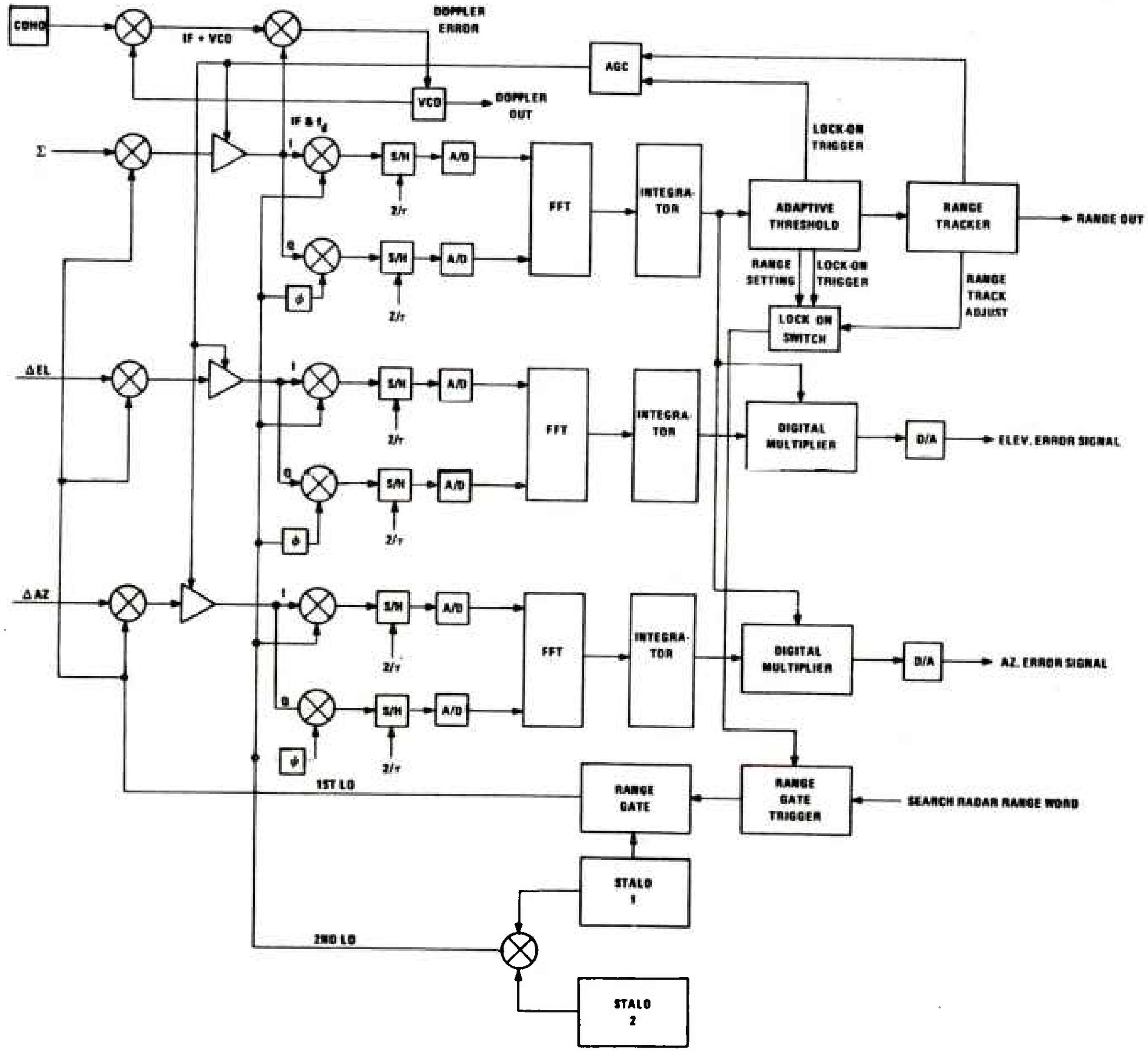

Figure 12. Track receiver without pulse staggering circuits.

All three designer channels are designed to produce coherent integration gain prior to error detection. The second LO is generated to reduce the carrier frequency to facilitate adequate FFT operation. The function of the FFT and integrator has been explained earlier in this report.

Once integration is completed, the azimuth and elevation errors are sensed in a ditital multiplier. The output of the multiplier is subjected to D/A conversion and then is applied to servosignal-conditioning circuits, which are not shown.

The doppler signal is tracked by means of a VCO to null the doppler frequency. Once the doppler error is zero, the VCO delivers an output signal representative of doppler.

A key element to both the acquisition and the track modes is the adaptive threshold circuit. The adaptive threshold circuit is required to perform several functions, including those of the lock-on, and range adjustment triggers and switching. Its most important function, however, is its capacity to vary the signal detection threshold over the noise. The adaptive threshold achieves this by measurement of the average noise power and by adjustment of the signal level accordingly.

The configuration of the track mode as well as the acquisition mode is complicated by such items as PRF staggering.

Track Radar System Considerations

The elements of the track radar configuration are those that deal with the function of the transmitter, the PRF staggering, the display, and tactical considerations. These items are discussed in the succeeding subsections.

Transmitter

The transmitter to be implemented should be coherent and should include PRF staggering consistent with the receiver. A typical transmitter implementation for coherent operation is illustrated in figure 13.

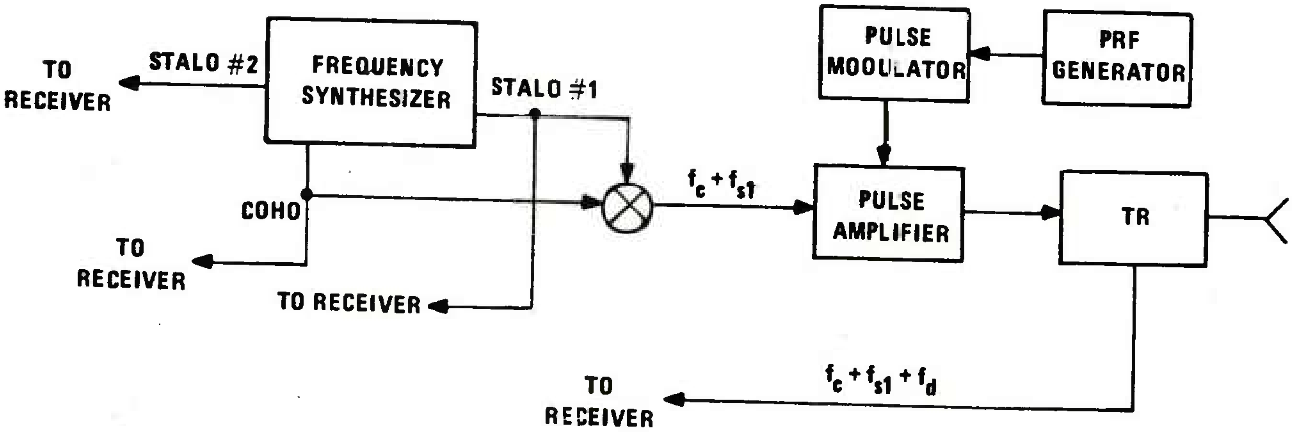

Figure 13. Typical transmitter implementation for coherent operation.

The only differenee, although a significant one, between the implementation block diagram shown in the figure and a potential 94-GHz transmitter is the lack of any coherent oscillator at 94 GHz. Consequently, some form of frequency multiplication is required to reach 94 GHz. In the case of pulse-to-pulse staggering, the implementation must be altered.

Pulse-to-Pulse Stagger

Earlier in this report, four-pulse stagger was determined to represent the optimum PRF jitter in terms of frequency response and blind-speed removal. The four PRF's selected were: 10.8 kHz, 10 kHz, 8.8 kHz, and 8.4 kHz. For the purpose of the following discussion, the time delay required to generate each PRF shall be designated 0, T_1, T_2, and T_3, respectively.

A convenient method of implementing the PRF stagger is shown in figure 14. Note that, as the switch is moved from one position to another, the duty cycle encounters a long-short-long-short sequence that eases the strain on the pulse amplifier. When the switch is in the position shown, the PRF is delayed for the maximum time that corresponds to 8400 Hz. With the maximum delay present in the transmitter, the minimum delay must be present at the receiver to achieve the same time of occurrence for the pulses at the receiver. The length of the delays is such that at any switch position, the time of occurrence of the pulses at the receiver is equal to the delay time, T_3. This is due to the relationship between the delays in the ratio 27:22:25:21, or 10,800:8800:10,000:8400, or $0:T_2:T_1:T_3$.

The delays discuesed above may be implemented with tapped delay lines for both the transmitter and receiver. The major weakness of this implementation is the operating frequency difference between the transmitter and the receiver. A better method of implementation may be the application of a common processor to generate the four PRF's at the proper time intervals.

Display

Although the later development of this radar concept will require a rather sophisticated display, an A-scope should be adequate for the purposes of demonstration.

Tactical Considerations

A major weakness of the 0.5 degree by 0.5 degree track beam is the small volume illuminated. An aircraft flying a course across the track beam at a Mach I velocity has an excellent opportunity to escape the beam volume prior to acquisition. At 7 kilometers, the track beam is only 280 meters wide. A Mach I aircraft could traverse this distance in less than 1 second.

One approach to circumvent this problem is to utilize a dual frequency track system that could provide greater spatial coverage.

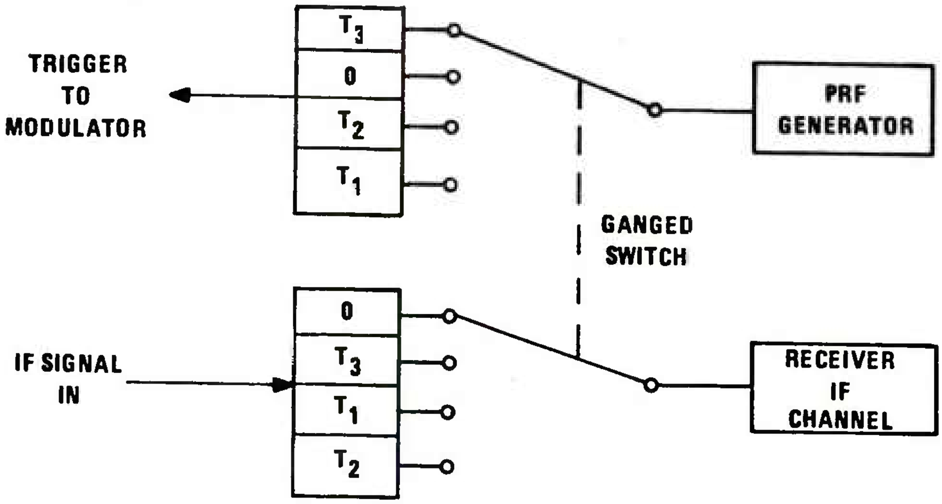

Figure 14. Implementation of four-pulse PRF stagger.

Another option is to have a track-while-scan capability in the search radar to supplement the track radar. TWS has the additional advantage of being able to track multiple targets.

Recommendations

The track radar should be an amplitude comparison monopulse system. The IF strip in each track channel should contain a digital filter bank, implemented with an FFT and integrator to provide 20 dB of clutter rejection and coherent integration of 100 pulses. Such an IF channel will allow a lower required S/N threshold due to the detection scheme utilized that requires one detection in three looks.

An adaptive threshold should be provided to overcome barrage jamming through the sidelobes.

The AGC loop should have at least a 70 dB dynamic range to provide constant gain from the desired acquisition range of 7.5 kilometers to 200 meters.

The antenna should be a 0.6 meter disk in a Cassegrain configuration to reduce waveguide lengths.

Finally, the trade-offs between a track-while-scan system system and a dual frequency track system should be made to determine the optimal system configuration.

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